

Revisiting the characteristics of the spectral lags in short gamma-ray bursts ^{*}

Zhibin Zhang^{1,3}, G. Z. Xie¹, J. G. Deng², W. Jin^{1,3}

¹*Yunnan Observatory, National Astronomical Observatories, Chinese Academy of Sciences,
P. O. Box 110, Kunming 650011, China*

²*Physics Department, Guangxi University, Nanning, Guangxi 530004, P. R. China*

³*The Graduate School of the Chinese Academy of Sciences*

Accepted 0000. Received 0000; in original form 2006 April 10

ABSTRACT

In this paper, we restudy the spectral lag features of short bright gamma-ray bursts ($T_{90} < 2.6$ s) with a BATSE time-tagged event (TTE) sample including 65 single pulse bursts. The cross-correlation technique is adopted to measure the lags between two different energy channels. Meanwhile, we also make an investigation of the characteristics of the ratios between the spectral lag and the full width at half maximum ($FWHM$) of the pulses, called relative spectral lags (RSLs). We conclude that spectral lags of short gamma ray bursts (SGRBs) are normally distributed and concentrated around the value of 0.014, with 40 percent of them having negative lags. With K-S tests, we find the lag distribution is identical with a normal one caused by white noises, which indicates the lags of the vast majority of SGRBs are so small that they are negligible or nonmeasurable, as Norris & Bonnell have suggested.

Key words: gamma-rays:bursts – methods:data analysis

1 INTRODUCTION

The phenomena of SGRBs remained more mysterious than long ones until recently, owing to a lack of more information about observations such as afterglows. They have been found to be harder than long bursts in spectra (e.g. Kouveliotou et al. 1993; Hurley et al. 1992). The

^{*} send offprint request to: z-b-zhang@163.com

spectra for both types generally evolve with time (Liang & Kargatis 1996; Band 1997). Most long GRB pulses reach their maximum earlier in higher energy channels, called “hard-to-soft” evolution with positive spectral lags (Norris et al. 2000; Daigne & Mochkovitch 2003; Chen et al. 2005), while the issue of SGRBs on spectral lags is still controversial, though some timescale analysis techniques (Scargle 1998; Liang et al. 2002; Li et al. 2004) have been employed to improve it.

The distribution characteristics of SGRB spectral lags had previously been explored by several authors. We can divided their viewpoints into two typical cases: one is that Norris et al. (2001, 2006) found the time lags in SGRBs were close to symmetric about zero and confirmed they could be negligible in statistics. Another is that Gupta et al. (2002) studied the lags with a sample of 156 SGRBs and found that one quarter of the total had negative lags, implying “soft-to-hard” spectral evolution. Recently, using a sample of 308 SGRBs, Yi et al. (2006) redid the analysis of time lags and conclude that the sources with negative spectral lags are in the minority (only about 17 percent of sources in their sample locating at the side of negative lags). Prompted by the contradictory results, we thus want to research what the features of the spectral lags in SGRBs should in essence be. To avoid the contamination of adjacent pulses by overlap, which could inevitably produce additional errors owing to selection effects, we construct our sample from SGRBs with single pulses in order to calculate the unbiased lags accurately.

We have shown in our recent work (Zhang et al. 2006, hereafter paper I) that the RSL of long bursts can be used as a good redshift estimator. Since pulse widths and spectral lags are respectively proportional to Γ^{-2} approximately (Qin et al. 2004; Zhang & Qin 2005 and paper I) and the relationship of them with energy is roughly $\sim E^{-0.4}$ (Fenimore et al. 1995; Norris et al. 1996), such a definition of RSL can eliminate the influence of Lorentz factor and energy on our analysis and thus the RSL could be regarded as an intrinsic parameter. Considering this virtue, we expect to know what the distribution of RSL should be. In §2 we give the data preparation; Definitions and measures of the physical variables are shown in §3; We list our new results in §4. We end with a brief conclusion and discussion in §5.

2 DATA PREPARATION

2.1 Sample selection

Considering the duration attribute of SGRBs, the high-resolution TTE data at 5 ms resolution are adopted to constitute our sample, including 65 bursts. This sample consists only of single peaked bursts. The motivation for this selection is that spectral lag analysis is usually affected by both energy channel pair and time resolution, as well as the neighbor pulses due to overlapping effects. More detailed explanations for this can be found in paper I. Consequently, the selection requirements in terms of the above considerations are given as follows: T_{90} duration < 2.6 s; BATSE peak flux (50-300 keV) > 2 photons $cm^{-2}s^{-1}$; and also peak count rate (> 25 keV) > 14000 counts s^{-1} . Certainly, a bright-independent analysis is required as the requirement for burst duration measurement (Bonnell et al. 1997) and the signal-to-noise (S/N) levels are also taken into account, so that we can take more relatively accurate measurements of such variables as width and spectral lag of pulses.

2.2 Background subtraction

The first step is to select an appropriate background for subtraction. In terms of the existing opinion (e.g. McBreen et al. 2001), the median filter method is suitable for background subtraction of SGRB data because of their special duration and background level. Firstly, the start and end times in each pulse are determined. The section involving pre- and post-pulse is generally regarded as background. With the median method, the corresponding median within the range of background data points is easily estimated. Secondly, the estimated value of the background is subtracted from the whole original data. According to this methodology, we apply the same measurement to perform this analysis of subtraction for all four energy channels (channel 1, 20-50 Kev; channel 2, 50-100 Kev; channel 3, 100-300 Kev; channel 4, >300 Kev) respectively.

2.3 Denoising

After the background in each channel is subtracted the remaining data are still fluctuating because of the disturbance of noise. In theory, we must smooth these rough data in order to obtain the pure signal data for the sake of analysis. For one burst, we hence adopt the following model describing the pulses' shape (Kocevski et al. 2003) to fit the disturbed data

$$F(t) = F_m \left(\frac{t}{t_m} \right)^r \left[\frac{d}{d+r} + \frac{r}{d+r} \left(\frac{t}{t_m} \right)^{(r+1)} \right]^{-\frac{r+d}{r+1}} \quad (1)$$

where t_m is the time of the maximum flux (F_m), of the pulse and the quantities of r and d are two parameters depicting the pulse shape. It has been shown that this function is very flexible and powerful for describing a single peaked pulse.

We find from this model that there are four fitted parameters. In fact, the exact function used to do the model fitting should include an additional free parameter, t_0 , denoting the start time of a pulse. The application of this zero parameter is advantageous to our analysis, because it can quicken the fit process and optimize the results. Once we have finished the disposal of noise, the original data are then refined into the usable signal data, which can be utilized to calculate the spectral lags and widths of pulses, as well as other physical quantities.

3 QUANTITY DEFINITIONS AND MEASURES

3.1 Spectral lag

To get the spectral lag, we cross-correlate variation signals in different energy channels j and k with the following cross-correlation function (CCF) (Band 1997)

$$CCF(\tau; v_j, v_k) = \frac{\langle v_j(t) v_k(t + \tau) \rangle}{\sigma_{v_j} \sigma_{v_k}} (j > k) \quad (2)$$

where $\sigma_{v_i} = \langle v_i^2 \rangle^{1/2}$, and i stands for the i^{th} energy channel; τ is the general spectral lag between energy bands j and k , namely τ_{jk} ; v_j and v_k represent two time series in which they are respective light curves in two different energy bands.

The value of τ_{jk} is determined by the location of τ where CCF peaks, because the CCF curve caused by smoothed signal data is considerably smooth and resembles a gaussian shape near its peak on this occasion. If the data points around the peak are sparse enough, we interpolate them in its neighborhood in order to reduce the calculation errors.

3.2 Relative spectral lag

For long bursts, wider-pulse bursts had been found to preserve longer spectral lags (Norris et al. 2005). This conclusion seems to be universal not only for long bursts but also for short ones. In addition, the same law about the relation of time lags to pulse width also seems to coexist between distinct energy channels within a burst. We thus are inspired to probe how

their ratios evolve with energy and other relevant parameters with the variety of spectral lags and widths. For this purpose, unlike in paper I, we redefine the quantity RSL as

$$\tau_{rel,jk} = \tau_{jk}/FWHM_{(k)}(j > k) \quad (3)$$

where $FWHM_{(k)}$ denotes the full width at half maximum of the time profile in the k^{th} discriminator. From the definition, one can see that $\tau_{rel,jk}$ is connected with the pair of energy channels and is indeed a dimensionless quantity.

Here, the values of the subscript k are assigned to be 1, while another subscript j , denoting a higher energy channel, is taken as $j = 3$. Although $FWHM_{(k)}$ are usually dependent on τ_{jk} , the relationship doesn't influence our analysis on its credibility (see paper I). If they are precisely measured, the corresponding RSLs can be well determined within a certain significance level.

4 RESULTS

After the subscripts in eqs. (2) and (3) are assigned as $k = 1$ and $j = 3$, combining eqs. (1)-(3) we can then derive the quantities, such as the spectral lag (τ_{31}), the width ($FWHM_{(1)}$) and the RSL ($\tau_{rel,31}$). In the following section, we study the properties associated with the above quantities of SGRBs, and list our results comparatively.

4.1 The distribution of τ_{31}

In the case of single peaked SGRBs, we make a plot in figure 1 in order to gain the spectral lag distribution, from which we find the lags have a distribution which is close to symmetric about zero. The distribution looks like a gaussian function outline. In order to prove this, we try to fit the distribution with a gaussian model and obtain $\chi^2/dof = 1.5$ with $R^2 = 0.98$, which indicates that the spectral lags are indeed normally distributed with a high confidence. Additionally, we find from figure 1 that the number ($\sim 40\%$) of SGRBs with negative lags are slightly less than those with positive values.

It is well known that white noise (random errors) can also lead to a normal distribution with the expectation value $\mu = 0$. Thus, our task in this situation is to check if the gaussian distribution of the spectral lags is in agreement with the distribution caused by noise taken as $\mu = 0$ and $\sigma = 0.1$. Figure 2 shows the comparison between them. We apply a general K-S test to the two one-dimensional distributions. Surprisingly we discover that they are in excellent agreement with each other, with large confidence probability $P \sim 0.82$ and small

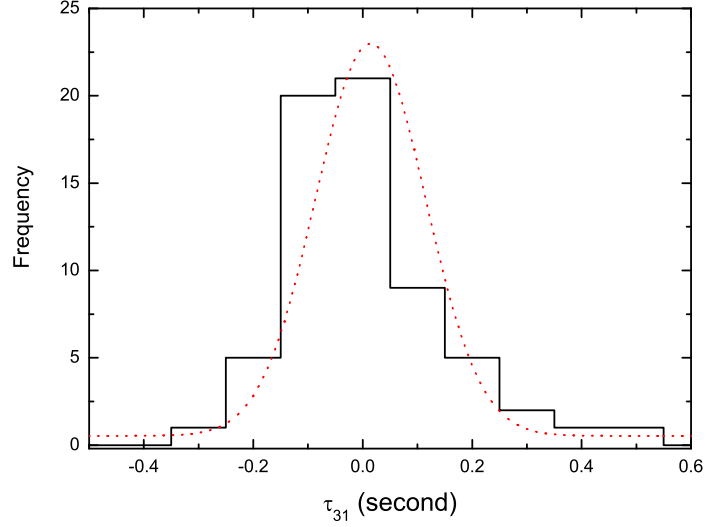


Figure 1. Distribution of spectral lags for a sample including 65 single peaked SGRBs. The dotted line represents the best fit to the distribution with a gaussian function, where the expectation value and the standard deviation are $\mu = 0.014$ sec and $\sigma = 0.1$ sec respectively. Fewer sources (40%) with negative lags, in contrast with those with positive lags, have a short tail of the population lying to the left-hand side of zero.

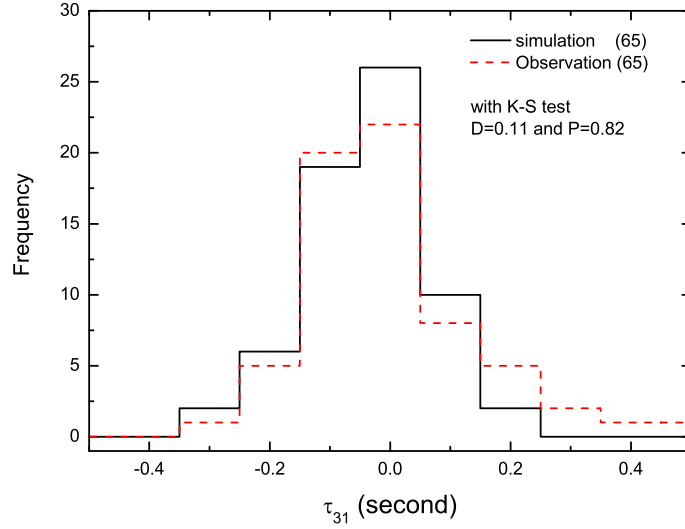


Figure 2. Comparison between the distribution of spectral lags in SGRBs and that of white noises. The sample size for both of them is equally 65. The former is marked with dashed line and the latter is identified by solid line. Symbols have been denoted in this plot.

K-S statistic $D = 0.11$. Furthermore, we find there are about 94% of the total sources which have zero lag within a 3σ fiducial limit. These results highly support the conclusion of a larger majority (90-95%) with nought lag drawn by Norris & Bonnell (2006).

The coincidental results demonstrate that the spectral lags of SGRBs are so small that

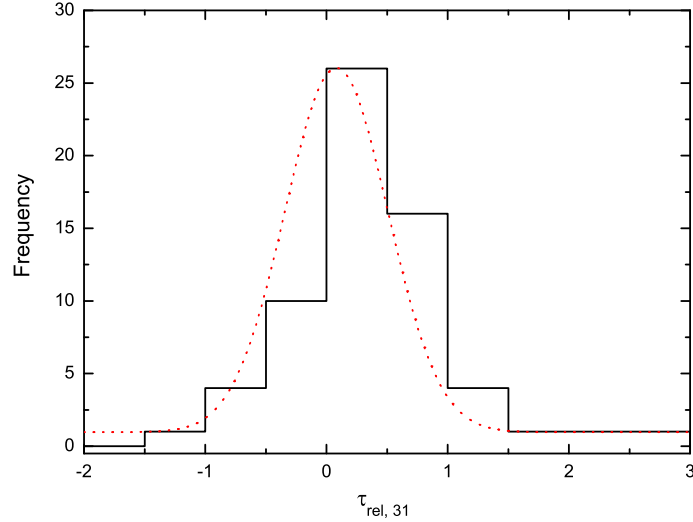


Figure 3. Distribution of RSL ($\tau_{rel,31}$) for a sample of 65 single peaked SGRBs. The dotted line represents the best fit to the distribution with a gaussian function, where the expectation value and the standard deviation are $\mu = 0.082$ and $\sigma = 0.42$ respectively.

they are comparable with random errors. The reason the lags follow such a normal distribution is probably that the tiny lags have been hidden just inside the random error bars or their magnitudes are smaller than the sensitivity limits of the detectors, which leads us to conclude the lags in SGRBs are so insensitive to the measurement that they can be neglected in statistics.

4.2 The distribution of $\tau_{rel,31}$

It has been indicated that the widths and spectral lags of SGRBs in comparison with those of long ones are usually smaller, however, whether or not their ratios also follow the same law is an important issue. Without losing generality, we choose the RSL $\tau_{rel,31}$ as the τ_{rel} for this study. In answer to this question, we make a plot of this distribution in figure 3, where we find the RSLs are normally distributed with $\chi^2/dof = 1.06$ and $R^2 = 0.99$. The expectation value and the standard deviation are respectively $\mu = 0.082$ and $\sigma = 0.42$.

SGRBs behave similarly to long ones (see paper I) in the distribution of RSLs, except that they differ in aspects of deviation errors and expectation values. In evidence, the discrepancy in the two classes originates directly from the fact that unlike SGRBs most long bursts exhibit “hard-to-soft” evolution with positive spectral lags. Moreover, we notice that the standard deviation of SGRBs is about 10 times larger than for long bursts. If we take the

2σ sample RSL error as our confidence limit, we can then estimate the effective upper limit to be $2\sigma/\sqrt{n-1} \sim 0.05$, which is reasonably close to the value, 0.045, for the long burst sample. In principle, RSLs should be normally distributed around zero if only the width of SGRB pulses can be accurately measured. As shown in figure 3, the RSL distribution indeed exhibits the trend although there is slight departure between theory and observation due to some calculation errors.

5 CONCLUSION AND DISCUSSION

Our main conclusions in this work are as follows: Firstly, spectral lags of SGRBs are normally distributed around zero, which causes many of them to be negligible or unobservable; Secondly, the RSL distribution is also found to be gaussian with the expectation value of 0.082.

According to the internal shock model, GRBs are generally produced by multiple relativistic shells (or wind) followed by internal shocks due to their collision as a central engine pumps energy into medium (see e.g. Fenimore et al. 1993; Rees & Mészáros. 1994). It has been shown that the bulk Lorentz factor increases linearly with radius until $\Gamma \leq 1000$ (Woods et al. 1995; Ramirez-Ruiz & Fenimore 2000; Eichler et al., 2000). Subsequently, the motion of the shocked ejecta would be decelerated by the action of the circumstellar medium (Huang et al. 1998, 2000; Piran 2005; Granot & Kumar 2006). However, the existence of discrete emission regions with incompatible velocities causes the collisions between them to be more intense and random. Because of the collisions of these shells, the forward shock and the reverse shock could be expected to occur at some distance from the central source, for instance $R \sim 10^{12-14}cm$ (Piran 1999), and propagate into the relativistic ejecta. Under these conditions, SGRBs with negligible spectral lags (due to large Lorentz factors) might take place. Norris & Bonnell (2006) had thought the high Lorentz factor, $\Gamma \sim 500 - 1000$, could interpret the phenomenon of negligible lags for SGRBs. If the dependence of spectral lags, τ , on Lorentz factor, Γ , can be also expressed as $\tau \propto \pm\Gamma^{-\omega}$ as in paper I, we can infer that either high Lorentz factors or large ω (e.g. $\omega \gg 2$), or both of them, could lead to smaller lags towards zero. In a word, the high Lorentz factor seems to be essential to this phenomenology.

Even though the statistical fluctuations and the spectral lags in SGRBs can produce the same normal distribution, the indistinguishable distributions couldn't exclude the smaller

lags in existence (Villasenor et al. 2005) if only lower energy bands (e.g. channel 1: 20-50 Kev) are taken into account (Norris & Bonnell 2006), since the contribution of curvature effects to spectral lags in this case would cause longer decays in pulses, and thus larger time lags. However, the influence of angular-spreading effects on the decay phase of pulses would be reduced with the decrease of radius of emission region. When the radii reduce to a certain limit, the curvature effects can then be eliminated. Under the circumstances, the time lags in GRBs should be unobservable. We hence deduce that SGRBs might locate at the smaller distance from the central engine.

Our findings in this paper are based on the previous observations of single pulse SGRBs. The conclusions need to be further verified by much more precise observations with the ongoing satellites HETE-2 and SWIFT, which would shed new light on the nature of spectral lags in SGRBs, even their physical mechanism and origin.

ACKNOWLEDGMENTS

We acknowledge the anonymous referee's helpful and constructive comments. We are also thankful to Dr R. S. Pokorny for his invaluable help.

REFERENCES

- Band D. L., 1997, ApJ, 486, 928
Bonnell J. T., Norris J. P., Nemiroff R. J. et al., 1997, ApJ, 490, 79
Chen L., et al., 2005, ApJ, 619, 983
Daigne F. & Mochkovitch R., 2003, MNRAS, 342, 587
Eichler et al., 2000, ApJ, 529, 146
Fenimore E. E., et al., 1993, Nature, 366, 40
Fenimore E. E., et al., 1995, ApJ, 448, L101
Granot J. & Kumar P., 2006, MNRAS, 366, L13
Gupta V., et al., 2002, astro-ph/0206402
Horváth I. et al., 2006, A&A, 447, 23
Huang Y. F., Dai Z. G. and Lu T., 1998, A&A, 336, L69
Huang Y. F., et al., 2000, ApJ, 543, 90
Hurley K., et al., 1992, AIP Conf.Proc., 265, 195
Kocevski D. & Ryde F. & Liang E., 2003, ApJ, 596, 389
Kouveliotou C., et al., 1993, ApJ, 413, L101
Li T. P., et al., 2004, ChJAA, 4, 583
Liang E. P., & Kargatis V. 1996, Nature, 381, 49
Liang E. W., Xie G. Z. and Su C. Y., 2002, PASJ, 54, 1
Mcbreen S., et al., 2001, A&A, 380, L31

- Norris J. P., et al., 1996, ApJ, 459, 393
- Norris J. P., Marani G. F. and Bonnell J. T. 2000, ApJ, 534, 248
- Norris J. P., Scargle J. D. and Bonnell J. T. 2001, astro-ph/0105108
- Norris J. P., et al., 2005, ApJ, 627, 324
- Norris J. P., & Bonnell J. T., 2006, ApJ, 643, 266
- Piran T., 1999, Physics Reports, 314, 575
- Piran T., 2005, astro-ph/0503060
- Qin Y. P., Zhang Z. B., Zhang F. W. et al., 2004, ApJ, 617, 439
- Rees M. J. & Mészáros P., 1994, ApJ, 430, L93
- Ramirez-Ruiz E., & Fenimore, E. E., 2000, ApJ, 539, 712
- Scargle J. D., 1998, ApJ, 504, 405
- Villasenor J. S., et al., 2005, Nature, 437, 855
- Woods E., et al., 1995, ApJ, 453, 583
- Yi T. F., et al., 2006, MNRAS, 367, 1751
- Zhang Z. B. & Qin Y. P., 2005, MNRAS, 363, 1290
- Zhang Z. B. et al., 2006, ChJAA, 6, 312; astro-ph/0603710 (Paper I)